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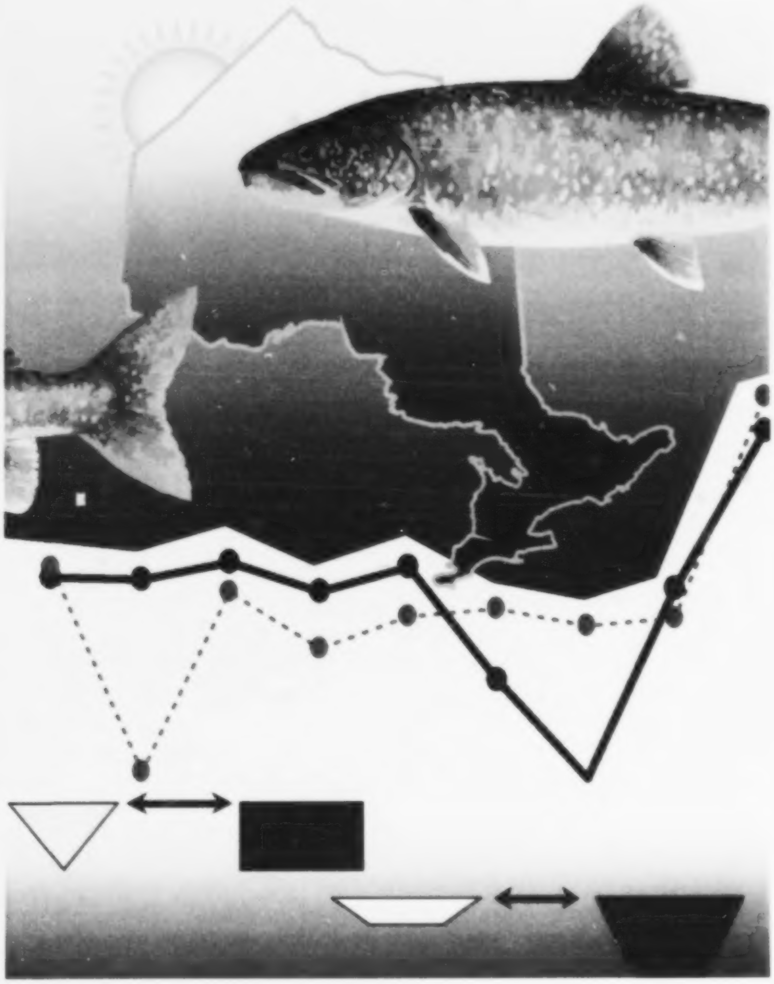
CLIMATE CHANGE RESEARCH REPORT
CCRR-14

Regional Projections of Climate Change Effects on Ontario Lake Trout *(Salvelinus namaycush)* Populations



Responding to Climate Change Through Partnership

Ministry of Natural Resources

Natural. Valued. Protected.

Ontario

Climate Change and MNR: A Program-Level Strategy and Action Plan

The following describes how the Ministry of Natural Resources works to contribute to the Ontario Government's commitment to reduce the rate of global warming and the impacts associated with climate change. The framework contains strategies and sub-strategies organized according to the need to understand climate change, mitigate the impacts of rapid climate change, and help Ontarians adapt to climate change.

Theme 1: Understand Climate Change

Strategy #1: Gather and use knowledge in support of informed decision-making about climate change. Data and information gathering and management programs (e.g., research, inventory, monitoring, and assessment) that advances our knowledge of ecospheric function and related factors and forces such as climate change are critical to informed decision-making. Accordingly, MNR will work to:

- Strategy 1.A: Develop a provincial capability to describe, predict, and assess the important short- (0-5 years), medium- (5-20 years), and long-term (20+ years) impacts of climate change on the province's ecosystems and natural resources.
- Strategy 1.B: Model the carbon cycle.

Strategy #2: Use meaningful spatial and temporal frameworks to manage for climate change. A meaningful spatial and temporal context in which to manage human activity in the ecosphere and address climate change issues requires that MNR continue to define and describe Ontario's ecosystems in-space and time. In addition, MNR will use the administrative and thematic spatial units required to manage climate change issues.

Theme 2: Mitigate the Impacts of Climate Change

Strategy #3: Gather information about natural and cultural heritage values and ensure that this knowledge is used as part of the decision-making process established to manage for climate change impacts. MNR will continue to subscribe to a rational philosophy and corresponding suite of societal values that equip natural resource managers to take effective action in combating global warming and to help Ontarians adapt to the impacts of climate change.

Strategy #4: Use partnership to marshal a coordinated response to climate change. A comprehensive climate change program involves all sectors of society as partners and participants in decision-making processes. The Ministry of Natural Resources will work to ensure that its clients and partners are engaged.

Strategy #5: Ensure corporate culture and function work in support of efforts to combat rapid climate change. Institutional culture and function provide a "place" for natural resource managers to develop and/or sponsor proactive and integrated programs. The Ministry of Natural Resources will continue to provide a "home place" for the people engaged in the management of climate change issues.

Strategy #6: Establish on-site management programs designed to plan ecologically, manage carbon sinks, reduce greenhouse gas emissions, and develop tools and techniques that help mitigate the impacts of rapid climate change. On-site land use planning and management techniques must be designed to protect the ecological and social pieces, patterns, and processes. Accordingly, MNR will work to:

- Strategy 6.A: Plan ecologically.
- Strategy 6.B: Manage carbon sinks.
- Strategy 6.C: Reduce emissions.
- Strategy 6.D: Develop tools and techniques to mitigate the impacts of rapid climate change.

Theme 3: Help Ontarians Adapt

Strategy #7: Think and plan strategically to prepare for natural disasters and develop and implement adaptation strategies. MNR will sponsor strategic thinking and planning to identify, establish, and modify short- and long-term direction on a regular basis. Accordingly, MNR will work to:

- Strategy 7.A: Sponsor strategic management of climate change issues.
- Strategy 7.B: Maintain and enhance an emergency response capability.
- Strategy 7.C: Develop and implement adaptation strategies for water management and wetlands.
- Strategy 7.D: Develop and implement adaptation strategies for human health.
- Strategy 7.E: Develop and implement adaptation strategies for ecosystem health, including biodiversity.
- Strategy 7.F: Develop and implement adaptation strategies for parks and protected areas for natural resource-related recreational opportunities and activities that are pursued outside of parks and protected areas.
- Strategy 7.G: Develop and implement adaptation strategies for forested ecosystems.

Strategy #8: Ensure policy and legislation respond to climate change challenges. Policy, legislation, and regulation guide development and use of the programs needed to combat climate change. MNR will work to ensure that its policies are proactive, balanced and realistic, and responsive to changing societal values and environmental conditions.

Strategy #9: Communicate. Ontarians must understand global warming, climate change, and the known and potential impacts in order to effectively and consistently participate in management programs and decision-making processes. Knowledge dissemination through life-long learning opportunities that are accessible and current is critical to this requirement. MNR will raise public understanding and awareness of climate change through education, extension, and training programs.

Regional Projections of Climate Change Effects on Ontario Lake Trout *(Salvelinus namaycush)* Populations

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Cette publication hautement spécialisée *Regional Projections of Climate Change Effects on Ontario Lake Trout (*Salvelinus namaycush*) Populations*. Pour obtenir de l'aide en français, veuillez communiquer avec le ministère de Richesses naturelles au information.ofri@ontario.ca.

Summary

We describe a simple method for mobilizing knowledge of physical limnology, lake geography, and thermal specialization among fish to generate spatially explicit forecasts of the effects of climate change on the habitat that can support particular species. We illustrate the approach by forecasting the effects of climate change on the amount of lake trout habitat distributed over Ontario's inland lakes for the period 1961 through 2100. Our forecasts suggest that by 2100 lake trout habitat will be reduced by about 30%, with steep declines (up to 60%) in the south and east only partly offset by increases (>30%) in the northwest. We argue that the forecasting capabilities provided by this method can be used to serve at least two purposes: (i) at the provincial scale, broad forecasts of how effects are expected to differ across regions would provide essential input for developing long-term management strategies; and (ii) at the regional scale, the ability to provide rapid and inexpensive re-assessments of potential effects would allow for timely revisions of local management tactics in response to revised climate forecasts.

Résumé

Projections régionales sur l'incidence du changement climatique sur les populations de touladis (*Salvelinus namaycush*) de l'Ontario

Nous décrivons une méthode simple pour exploiter les connaissances sur la limnologie physique, la géographie des lacs et la distribution des poissons selon la température de l'eau pour produire des projections spatiales précises sur l'incidence du changement climatique sur l'habitat de certaines espèces. Nous illustrons cette méthode en prévoyant les effets du changement climatique sur l'étendue de l'habitat du touladi dans les lacs intérieurs de l'Ontario de 1961 à 2100. Selon nos prévisions, l'étendue de l'habitat du touladi aura diminué de 30 % en 2100, avec un recul prononcé pouvant atteindre 60 % dans le sud et l'est qui ne sera que partiellement compensé par une augmentation de >30 % de l'habitat dans le nord-ouest de la province. Nous soutenons que cette méthode prévisionnelle peut servir d'au moins deux façons : (i) à l'échelle provinciale, des prévisions globales sur la variabilité des effets selon les régions pourraient contribuer à l'élaboration de stratégies de gestion à long terme; (ii) à l'échelle régionale, la capacité d'évaluer rapidement et à peu de frais les effets possibles du changement climatique permettrait d'adapter les tactiques locales de gestion aux prévisions climatiques changeantes.

Acknowledgements

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Introduction

Future changes in climate will affect the annual water temperature cycles of Ontario lakes. Assuming the climate warms as expected, surface waters will be warmer for longer periods in spring, summer, and fall reducing winter duration (Figure 1). Concurrently, stratification periods will increase, with negative effects on deep water oxygen levels in late summer leading to increased risk of summer kill events for many aquatic species.

Such changes in the seasonal water temperature pattern of a lake will have profound effects on the resident fish populations. The species of fish that live in the temperate lakes of Ontario can be classified based on the relatively narrow range of temperatures (≈5 °C) over which they are able to interact optimally with their environment. Three major groupings, or guilds, exist with optimum temperatures in (or near) the following ranges: the cold water guild at 9 to 14 °C (e.g., lake trout [*Salvelinus namaycush*]), the cool water guild at 18 to 23 °C (e.g., walleye [*Sander vitreus*]), and the warm water guild at 26 to 31 °C (e.g., largemouth bass [*Micropterus salmoides*]).

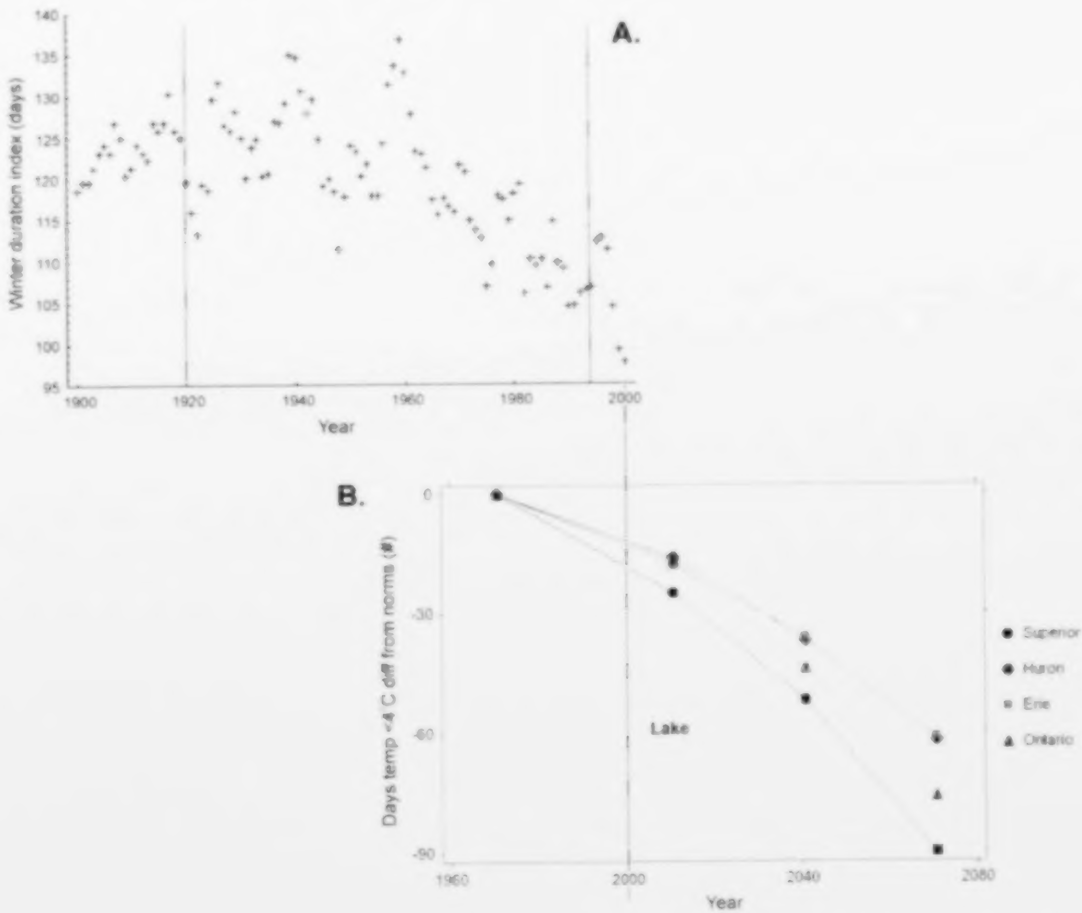

Figure 1. *Changes in the winter duration index (= number of days surface water temperatures are ≤4 °C) for the western basin of Lake Erie. (A) Changes from 1900 to 2000; each point represents a 5-year running average (Jones et al. 2006) of annual values. The running average is used to suppress short-term variation and reveal any long-term trends. (B) Projected future changes (Trumpickas et al. in press) based on the International Panel on Climate Change (IPCC) A2 greenhouse gas forecast scenario evaluated using the Canadian Global Climate Model version 2 (CGCM2) (see details in methods).*

The species-specific sustainable harvest for a lake (kg $year^{-1}$) depends directly on the amount of habitat that is thermally suitable for the species in question (Christie and Regier 1988). This is defined as the annual average amount of habitat space that exhibits temperatures that fall within the optimal range for the species. This quantity depends on three critical elements: the optimum temperature range for the species, the annual thermal stratification cycle for the lake, and the morphometry (i.e., size and shape) of the lake (Figure 2). The annual thermal stratification cycle for a lake depends primarily on its morphometry and local climate.

The critical elements that underlie this view of how climate, lake geography, and physiological specialization determine sustainable fish harvests in freshwater lakes have been the subject of extensive research in North America and elsewhere for the last 50 years (e.g., Wismer and Christie 1987). The detailed knowledge accumulated over this period is sufficient (e.g., Magnuson et al. 1990, Stefan et al. 2001) to generate first-order regional projections of climate change effects on sustainable harvests for a number of species that support economically important fisheries in Ontario. We use this approach to assess possible impacts of climate change on Ontario lake trout populations for the period 2000 to 2100.

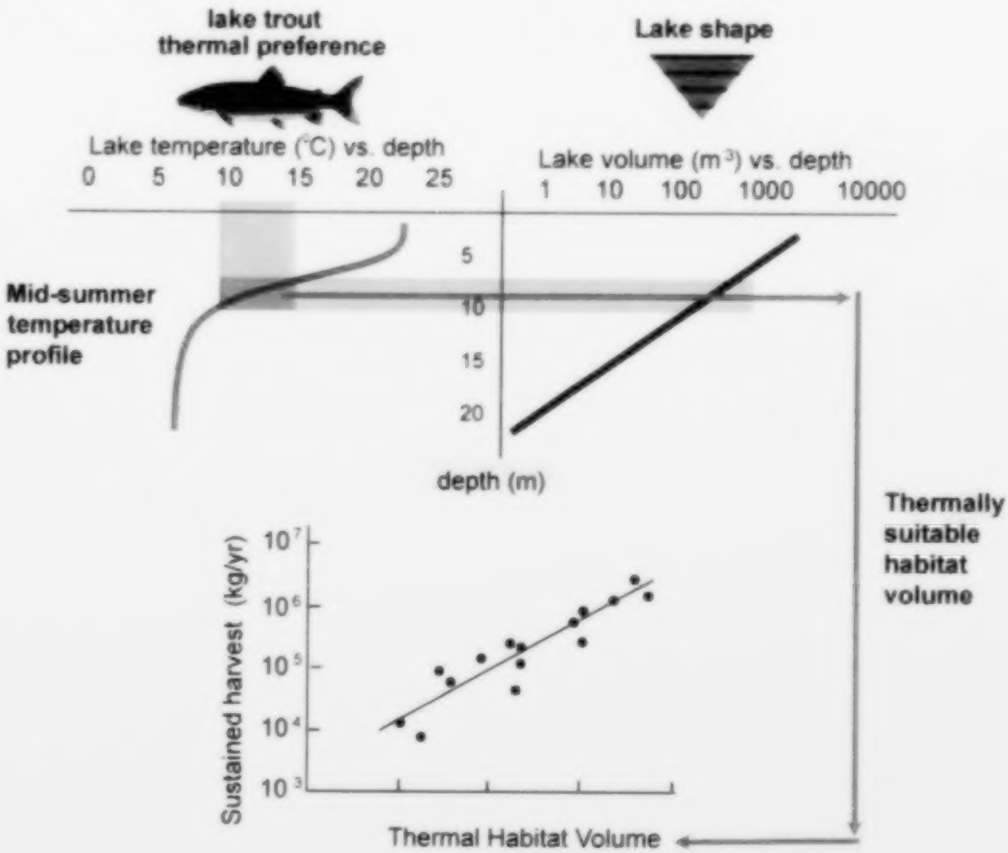

Figure 2. Schematic illustrating how to estimate the amount of species-specific optimal habitat available in a particular lake, with green bands and arrows illustrating how the three types of information are linked to generate the estimate. The preferred temperature range for the species and the summer temperature profile for the lake are used to identify the range of depths with preferred summer temperatures. The lake's volume-depth curve is then used to determine the volume of water in the preferred depth interval. This type of habitat measure can be used to estimate sustainable harvest levels as illustrated in the final graph (re-drawn from Christie and Regier 1988).

Methods

Our assessment of potential effects of climate change on lake trout is based on (i) regionally specific projections of future Ontario climate, (ii) regionally specific characterizations of the morphometry typical of Ontario lake trout lakes, (iii) validated empirical models of how changes in climate will be shaped by lake morphometry to determine future lake specific stratification patterns, and (iv) the temperature range supporting optimal performance of lake trout. Each element is described in detail below.

Future Ontario Climates

We used the 30 year 'average' Ontario climate for the period 1961 to 1990 as the reference climate. Future climates are 30-year 'average' climates for the periods 2011-2040, 2041-2070, and 2071-2100 (Figure 3) generated by the Canadian Global Climate Model v. 2 (CGCM2; Flato et al. 2000, Flato and Boer 2001) under the International Panel on Climate Change (IPCC) A2 emissions scenario (Nakicenovic et al. 2000). The A2 emissions scenario assumes relatively high and increasing greenhouse gas emission rates over the entire period from the present to 2100. For convenience, we refer to each of these climates by the mid-point of the time period they cover: 1975, 2025, 2055, and 2085, respectively.

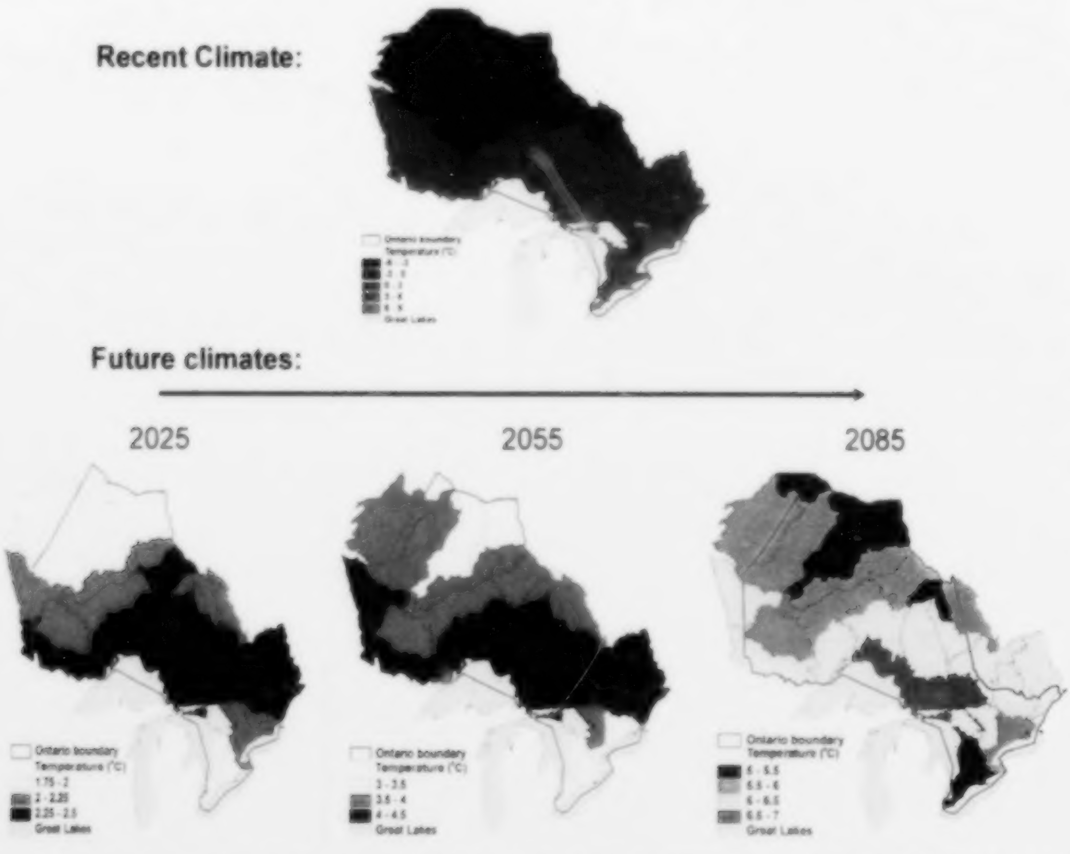

Figure 3. *Recent and projected future climates for Ontario based on the IPCC A2 scenario generated using CGCM2 (see details in text). In the Recent Climate map, differences in shading reflect differences in mean annual air temperature typical of the period 1961 to 1990. In the Future Climate maps, differences in shading indicate variations in projected increases in mean annual air temperature (from the 1961 to 1990 baseline) across Ontario for three points in time between 2000 and 2100. Ontario secondary watersheds are marked by thin solid lines and the Ontario political boundary is marked by the solid red line. Note the changes in colour coding for each of the future climate maps.*

Morphometry of Ontario Lakes and Presence/Absence of Lake Trout

Minns et al. (2008) developed a comprehensive accounting of Canadian lakes generally and lake trout lakes in particular. For each secondary watershed in the country, they assessed the morphometry of a typical lake (Figure 4) and the number of lakes in each of several lake size classes (0.1 to <0.2, 0.2 to <0.5, 0.5 to <1, 1 to <2, 2 to <5, 5 to <10, 10 to <20, 20 to <50, 50 to <100, and >100 km²). They also estimated the percentage of lakes containing lake trout (Figure 5), the sum of the surface area of all lake trout lakes, and the sum of the volume of all lake trout lakes in each lake size category in each secondary watershed. Our assessment uses these statistics for the secondary watersheds of Ontario.

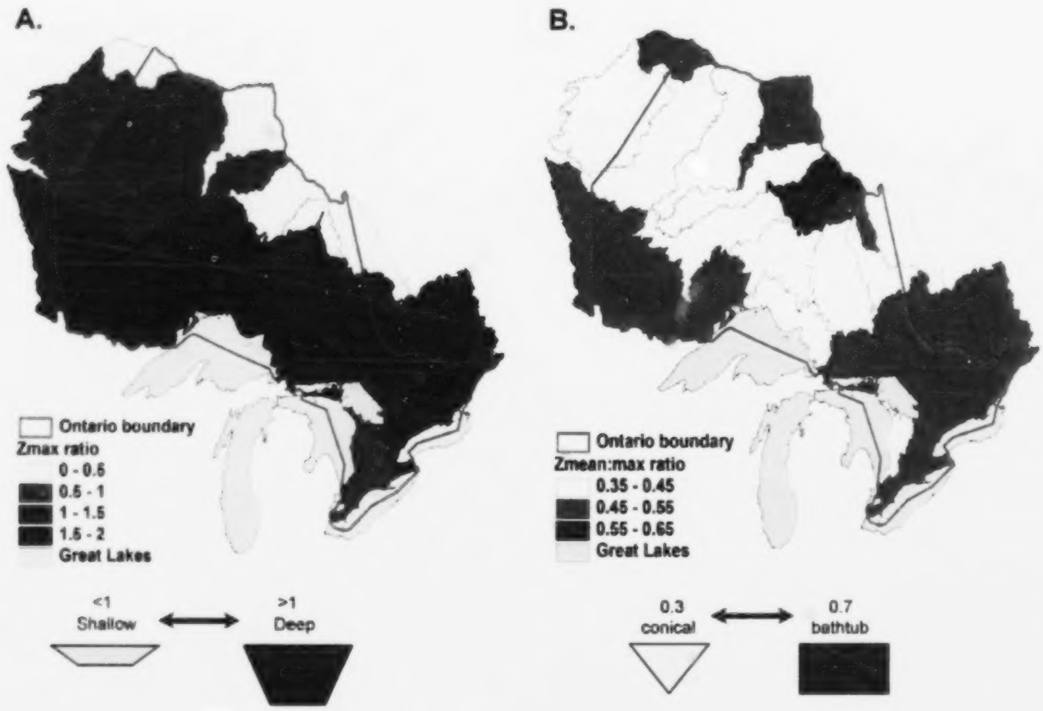

__Figure 4.__ Regional differences in two aspects of lake morphometry. (A) Shading reflects differences among secondary watersheds in typical values for maximum lake depth; units for the colour scale are based on the cross-Canada mean value for maximum lake depth (= 18.3 m): lakes with values >1 are deeper than the Canadian mean and those with values <1 are shallower. (B) Shading reflects differences among secondary watersheds in the typical value for the mean depth: maximum depth ratio; smaller values indicate a conical shape while larger values indicate a bathtub shape. Ontario secondary watersheds are marked by thin solid lines and the Ontario political boundary is marked by the solid red line.

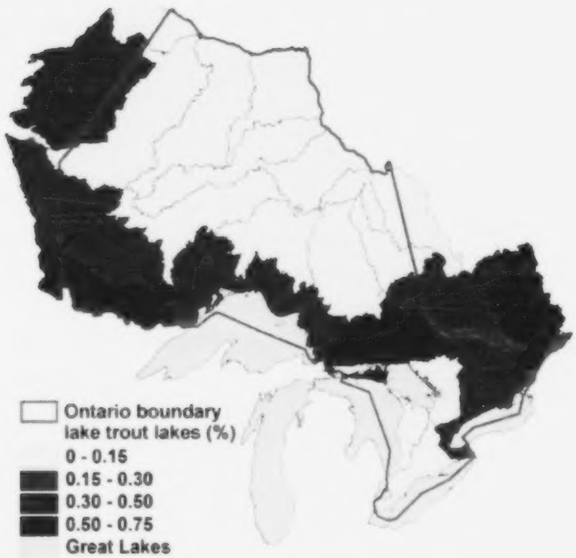

Figure 5. *Regional differences among Ontario secondary watersheds in lake trout occurrence. Shading reflects differences in the percentage of lakes within a watershed that support lake trout populations. Ontario secondary watersheds are marked by thin solid lines and the Ontario political boundary is marked by the solid red line.*

Estimating Lake Stratification Patterns

Some lakes develop distinct temperature-depth stratification patterns over the summer while others do not. The presence/absence of stratification is a key element in predicting the midsummer thermal profile of a lake and it is this profile that drives our estimate of the amount of lake trout habitat provided by a particular lake.

Our predictions of midsummer thermal profiles in lakes were based on four empirical models that predict (i) the maximum summer surface temperature (T_{max}), (ii) which lakes do and do not stratify, (iii) the temperature profile below the midsummer maximum for lakes that stratify, and (iv) the temperature profile below the midsummer maximum for lakes that do not stratify.

The model for predicting T_{max} is a simple function of mean summer (June-August) air temperature, latitude, and lake area. The model produces results comparable to models previously published by Shuter et al. (1983) and Sharma et al. (2007) and also to temperatures reported by Bussières et al. (2002) and Bussières and Schertzer (2003) for a number of large Canadian lakes.

We extended the approach of Mackenzie-Grieve and Post (2006) to model both the presence/absence of stratification and the shape of temperature profiles in both stratified and unstratified lakes. We used their model to assess the shape of summertime temperature profiles for a range of lakes in Ontario, British Columbia, and Alberta. Lakes were classified as *stratified* if they exhibited a sharp decrease in temperature several metres below the lake surface, and as *unstratified* if they were isothermal or exhibited a linear decrease in temperature from the surface to the bottom. Logistic regression analysis of these classified data provided a simple empirical model that could be used to predict whether a lake would stratify based on its area and maximum depth. Results from this model were similar to those previously reported by Hanna (1990). For stratified lakes, the temperature profile could be predicted with a separate empirical model based on lake area and maximum depth, a measure of water transparency (secchi depth), and local climate. For unstratified lakes, the temperature profile could be predicted with an empirical model based on lake area, maximum lake depth, and local climate.

Thermal Specialization of Lake Trout

Over the last 30 years, many investigators have evaluated the thermal performance of lake trout under laboratory conditions (see Wismer and Christie 1987). Most of these studies suggest that lake trout performance is optimal in the 8 to 12 °C temperature range. However, field studies documenting the water temperatures inhabited by lake trout in the wild show that individual fish are often found at temperatures outside this range (e.g., Morbey et al. 2006) even when areas with water temperatures within the range are available. In addition, recent laboratory performance studies (McDermid 2007, McDermid et al. 2007) have shown that lake trout from wild populations that experience very different ecological conditions exhibit systematic differences in both their life history characteristics and their thermal optima (Figure 6). These findings suggest that the thermal optima of different lake trout populations may be locally adapted to their current climate, perhaps exhibiting a greater degree of specialization than previous studies would indicate. Following the results of McDermid (2007), we chose to evaluate how current levels of habitat suitable for four strains of lake trout with narrowly adapted temperature ranges (6-8 °C, 8-10 °C, 10-12 °C, and 12-14 °C) would be affected by climate change.

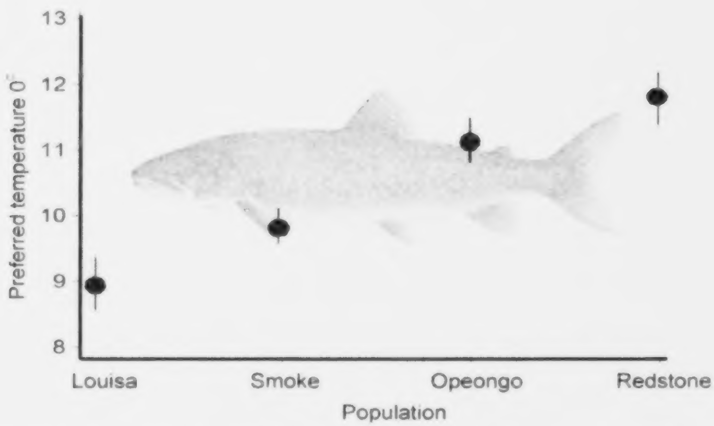

***Figure 6**. Differences in preferred temperature among 4 southern Ontario lake trout populations. Eggs from each population were collected in the wild, fertilized, then raised under similar laboratory conditions for 1 year. Thermal preference was assessed at the end of that year; dots specify mean values, bars give ± 1 std. error.*

Assessment of Impacts of Climate Change

Our assessment provides an explicit evaluation of the role that local adaptation of thermal optima may play in shaping how Ontario's lake trout populations will respond to climate change. This was done by carrying out separate, region-specific assessments for each of the four optimal temperature ranges noted above. Each assessment was carried out as follows: For each lake size category, within each secondary watershed (i) the typical midsummer thermal profile was estimated using the lake area and morphometry typical for the size category and the mean annual air temperature specific to the watershed, under a given climatic regime; (ii) the volume of optimal habitat at midsummer in a lake typical of the size category was estimated using this thermal profile plus the volume at depth curve typical for the lake size category plus the optimal temperature range under evaluation; (iii) the watershed total (km^3) for the volume of optimal habitat in the lake size category was then estimated by multiplying the estimated optimal volume per lake by the watershed-specific value for the number of lakes in the lake size category. Separate estimates were prepared for four separate points in time (1975, 2025, 2055, and 2085).

Results

Our analyses show that, under current climatic conditions, the amount of cold-adapted (6 to 8 °C = T6-8) lake trout habitat supported by Ontario's inland lakes is greater than the amount of warm-adapted (12 to 14 °C = T12-14) lake trout habitat (Figure 7a). This conclusion holds for all lake size categories; collectively however, warm-adapted habitat comprises a greater proportion of overall lake trout habitat (i.e., T6-8 + T8-10 + T10-12 + T12-14) in smaller lakes.

As the climate changes over this century, it is expected that cold-adapted lake trout habitat will shrink more quickly than warm-adapted lake trout habitat (Figure 7b). In addition, transitory increases in habitat for warm-adapted fish may occur in some lake size categories. However, by the end of the century, habitat for all thermal classes will be reduced by an average of 30 to 40% (Figure 7c), with more severe reductions in some lake size categories than in others.

As we have seen, projections for the province as a whole indicate an overall decline in lake trout habitat of 30 to 40% across all thermal classes. However, regional projections within Ontario tell a different story (Figure 8). Declines of 10 to 60% throughout the eastern and central parts of the province are countered by increases of up to 60% in the far northwest. Unfortunately, many of the areas where significant decreases in lake trout habitat are expected are those where much of that habitat now occurs. However, the three watersheds where habitat increases are expected are those that currently support significant amounts of habitat. With projected increases of up to 60%, these watersheds will provide a substantial refuge for lake trout in the province.

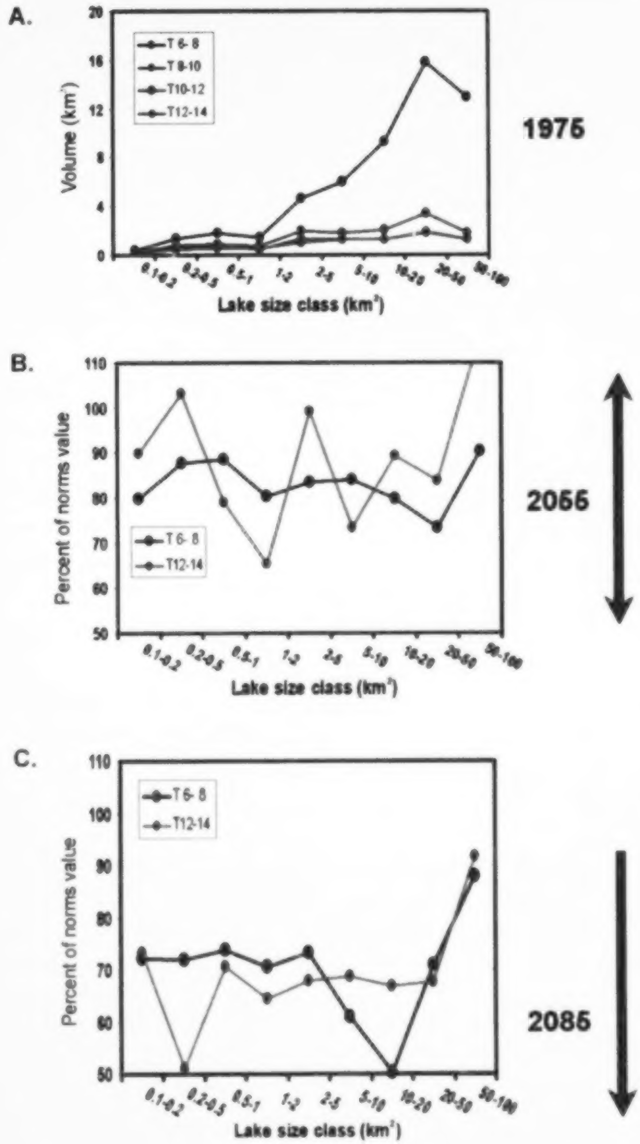

Figure 7. Current and expected future amounts of optimal lake trout habitat in Ontario. (A) Total volume (km³) of habitat by lake size category for four thermal classes under recent (1975) climatic conditions. The colour of the line identifies the optimal temperature range for the class. Size categories are based on the area of the lake. (B) Optimal habitat available in 2055, expressed as a percentage of the amount available in 1975. (C) Optimal habitat available in 2085, expressed as a percentage of the amount available in 1975. Climate forecasts are based on the IPCC A2 scenario using the CGCM2 climate model.

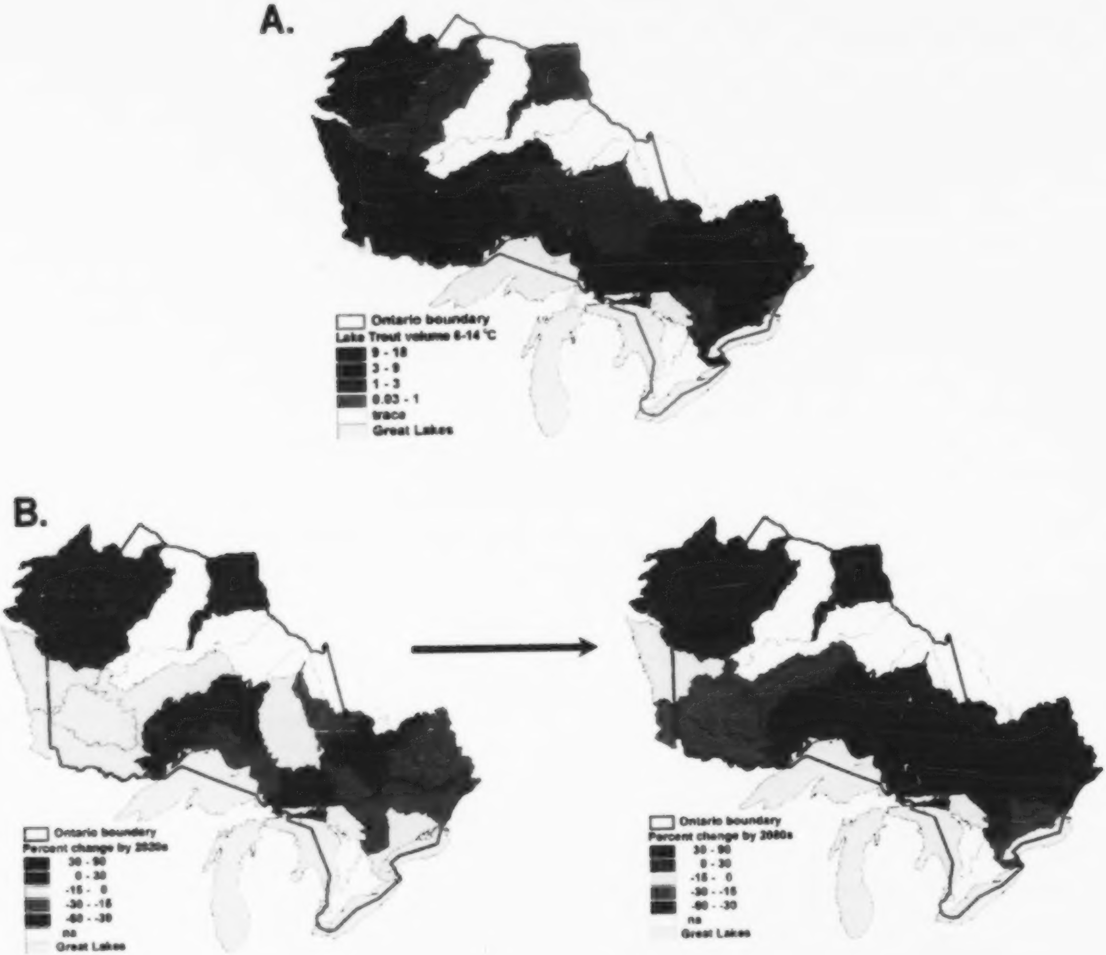

Figure 8. Regional differences in current and future amounts of lake trout habitat among Ontario secondary watersheds. (A) Total volume (km³) of preferred lake trout habitat by secondary watershed under recent (1975) climatic conditions. Values were obtained by summing across all four thermal classes. (B) Percentage changes in preferred habitat volume from 1975 levels under the climatic conditions forecast for 2025 and 2085, respectively. Climate forecasts are based on the IPCC A2 scenario using CGCM2. Ontario secondary watersheds are marked by thin solid lines and the Ontario political boundary is marked by the solid red line.

Conclusions

Our results suggest that, in the long term, total lake trout habitat for all thermal classes will shrink substantially (≈30 %). However, the amount of lost habitat will vary widely among lake size classes and geographic regions. The timeframe and spatial scale of these effects requires planning at spatial and temporal scales that are unfamiliar to most resource managers. For example, our forecasts contain *short-term* improvements for some thermal classes but *long-term* declines for all classes. However, in these forecasts, short term refers to intervals on the order of 2 or 3 decades while long term refers to an interval of a century or more. These timeframes contrast with current planning cycles, which typically operate over approximately 5-year intervals. Similarly, these forecasts vary regionally across the province. The locations of different *impact* regions are shaped by the presence of specific climatic zones and geological features (e.g., the Canadian Shield) and are only peripherally related to the position of political boundaries and concentrations of human populations – the factors that often shape planning regions.

These results raise a number of considerations for developing future strategies for both research and management of lake trout in Ontario:

(i) Habitat for warmer adapted classes of lake trout is proportionally more abundant in smaller lakes (Figure 7a). Therefore, studies designed to identify and characterize these thermal classes should focus on populations resident in smaller lakes.

(ii) Decreases in lake trout habitat will occur throughout the central and eastern parts of the province. Therefore, management strategies for populations located in these regions should focus on protective measures. Reduced optimal habitat does not necessarily imply local extinction: in the absence of warm-adapted competitors, persistent and continued (if reduced) human use may be possible. However, introduction of exotic (or native) warm-adapted competitors can quickly cause local extinction. Therefore, strategies for managing these lake trout populations should focus on reduced use, invasion protection, and recognition that in some cases local extinction is inevitable.

(iii) Progressive increases in lake trout habitat will be concentrated in the northwest of the province. Management strategies for populations located in these regions could focus on planned extensions of human use. This might involve carefully monitored increases in allowable harvest levels and assisted migration of lake trout into lakes where they do not currently reside.

In this report, we describe tools that can provide resource managers with a broad perspective on potential variation in the direction and timeframe for climate change effects across the province – the kind of information that is needed for long-term strategic planning. This approach can also be used to provide rapid, inexpensive assessments and re-assessments of potential effects at finer spatial scales. The need for rapid and inexpensive re-assessments is likely to be high because forecasts of future climates are expected to be updated frequently as the science improves and, more importantly, as it becomes clear how the world community chooses to manage greenhouse gas emissions. The approach outlined here can quickly translate new climate forecasts into updated effects forecasts. The reliability of these effects forecasts, and particularly whether they can be used to discriminate real differences at finer spatial scales, could be significantly improved through modest investment in (i) more precise descriptions of spatial heterogeneity in lake size/shape; (ii) more precise descriptions of how climate, water quality, and lake bathymetry interact to shape seasonal development of temperature and oxygen stratification in lakes; and (iii) more precise descriptions of thermal specialization within species of fish that are of particular concern to management.

Lake trout are the so-called poster-fish for boreal shield lake ecosystems (Gunn et al. 2004) and are a highly valued target of commercial, recreational, and Aboriginal fisheries. How well lake trout resources persist and thrive during the expected climate warming will be determined by the adaptation potential of the species, the care taken by resource users, and the judgement of ecosystem managers.

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